The CAA-MIT Microwave Instrument Landing System

E. L. BOWLES (FELLOW AIEE) W. L. BARROW (MEMBER AIEE) W. M. HALL (ASSOCIATE AIEE)

F. D. LEWIS (NONMEMBER AIEE) D. E. KERR (NONMEMBER AIEE)

THE PROBLEM of developing an instrument landing system in which the pilot is kept informed as to both his location and orientation by the indications of a single instrument was put to the Massachusetts Institute of Technology several years ago by I. R. Metcalf of the Civil Aeronautics Authority. The solution of this problem includes the application of centimeter waves, the development of a straight-line glide path, and the realization of a novel instrument combination. Intrinsically and because of recent trends in aircraft navigation these features, we believe, represent significant advances in the art. The experimental development described here in general outline was carried on under the sponsorship of the Authority and was built on MIT's background of research on the broad problem of navigation in fog and on work in the short-wave field per se as a foundation.[1] The apparatus was designed to demonstrate feasibility only. Commercial embodiment of the results is it is felt now within reach of the industry.

The General Problem

The problem as presented was based on the idea that a serviceable instrument landing system could be realized if, under conditions of no visibility, it were possible to present to the pilot the same information he would obtain were he to land on a clear night by means of three lights arranged on the landing field as shown in figure 1. These lights would indicate to the pilot in a simple, natural, and continuous manner not only his location but also his attitude and heading.

To visualize the problem in greater detail imagine the three lights as seen through a transparent screen in front of the pilot. Assume that the screen has vertical and horizontal cross hairs intersecting at its center. When the airplane is in the proper orientation for landing, and is on the reference landing path defined by the three lights as shown, the pilot sees these lights equally spaced along the horizontal cross hair, the center light coinciding with the center of the screen. Any departure of the lights from this pattern on the screen indicates a corresponding departure of the airplane from the proper location or orientation.

In the simplest interpretation, the location of the light group indicates orientation and the relative configuration of the lights as a group indicates location. Thus turning of the airplane to the right or left moves the lights as a group left or right respectively; moving to the right or left of the reference landing path moves the image of the center light nearer to the image of the right- or left-hand light respectively.*

The Metcalf problem then was to provide on the instrument panel of an airplane the same information indirectly by means of the visual image of three hypothetical lights with movements corresponding to those of the real light arrangement under corresponding conditions. The solution MIT proposed was to synthesize the image of the three hypothetical lights by a combination of radio- and gyro-instrument means. Information regarding orientation was to be derived from gyro instruments on the airplane, and information regarding location to be derived from electromagnetic radiation from transmitting means on the ground. The combined information was in turn to control three spots on the face of a cathode-ray tube used as the indicating instrument. This use of the gyro group suggested at once an instrument that could serve not only for landing but also for cross-country flying.

The radiation from the ground was to define a straight-line reference path down which the airplane could be flown at its normal glide angle. It is easier to control an airplane when landing at constant air speed and rate of descent, that is, when flying down a straight glide path than when following a curved glide path. Hence, aside from the fact that a straight-line path is inherent to the three-light landing procedure, from flying considerations alone, there is justification for a path of this form. The information must be given to the airplane as to whether it is above, below, to the right, or to the left of the reference path. It was planned to supply this information by the use of crossed or equisignal beams: one pair with separate modulations for the up-down information and a corresponding pair for the right-left information. Utilization of the equisignal beams made available the advantages of automatic volume control, including freedom from effects of change of received signal with antenna orientation, and of change in receiver sensitivity.

To the location information obtained from equisignal beams and the orientation information from the gyroscopic instruments† must be added distance information. Distance information, if it is desired to complete the three-light illusion, could be obtained from a signal intensity control moving the two outer spots on the indicating instrument farther apart as the landing field is approached, or it could be given independently by means of marker beacons.

The research resolved itself into two principal aspects, one dealing with the production of the instrument in the air-

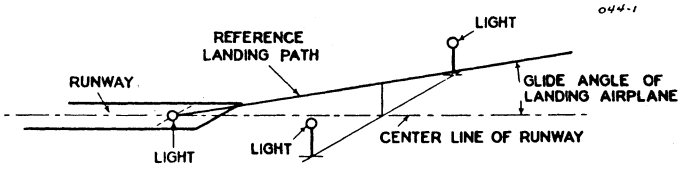

Figure 1. Arrangement of lights on landing field

Paper 40-44, recommended by the AIEE committee on communication, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted December 2, 1939; made available for preprinting January 5, 1940; released for final publication March 29, 1940.

E. L. BOWLES is professor of electrical communications and W. L. BARROW and W. M. HALL are assistant professors of electrical communications at Massachusetts Institute of Technology, Cambridge; F. D. LEWIS and D. E. KERR are associated with the same institution.

1. For all numbered references, see list at end of paper.

* During the study and testing of various approximations to the true image of the three lights on the landing field, the fact developed that the pilot, when landing in clear weather, makes use of the horizon as well as the view of the airport in front of him. It is possible to give the equivalent of this information by controlling the relative vertical positions of the outer two of the three spots on the instrument by means of the gyro-horizon alone and the center one by means of the landing reference path alone. The general behavior of the three spots will still conform to the basic principles set forth in the original problem.

† The heading information, it was contemplated, could also be obtained from a radio compass.

plane and the other with the production of the landing reference path. The rigid self-imposed requirement that this path should be substantially free from extraneous effects indicated concentrated beams and this in turn made it desirable to use as short a wave length as possible for beam energy. On the other hand the limitations of high-frequency commercial vacuum-tube equipment made it desirable initially to set 100 centimeters as the lower practical limit of this wave length. Although this wave length was much longer than desirable, it was hoped that as the research progressed the ultrahigh-frequency art would develop to a stage where generators and receivers of much shorter wave length would be available. In the experimental investigation wave lengths of the order of 50 centimeters were used for convenience with the idea that the data could subsequently be applied to the design of longer or shorter wave length radiators by the use of dimensional multiplication. Later promising developments in the art made it feasible to adhere to approximately 50-centimeter waves in all our work.

The possibility of using infrared radiation as well as radio waves to produce the reference path was also investigated. The MIT work on light penetration of fog had indicated that there was possibly a pass region in the spectrum between 8 and 12 microns. This possibility together with the feeling on the part of many that infrared waves offered a solution made it important to examine the applicability of infrared radiation. After investigation including experimental confirmation covering wave lengths out to 15 microns, the use of these long infrared waves was ruled out because of the unobtainable power that would be required to provide the desired range over a sufficiently wide field for this specific purpose.‡

The Instrument

The instrument aspect of the problem very quickly reduced itself to three divisions: the obtaining of electrical signals from the gyro instruments, the development of instrumental means of synthesizing the images of the three hypothetical lights for presentation to the pilot, and the study of approximations to the true image patterns that might be utilized as practical variations or simplifications.

A simple electrical take-off for obtaining signals from the gyroscopic instruments was sought and it was decided to investigate first the applicability of a voltage divider or slide-wire means whereby rotation of the gyro element would cause a fine wire brush to move across a resistor card and deliver a voltage of magnitude and sign proportional to angular displacement. Should this

Figure 2. Electrical take-off mechanism in one of the gyro units

idea prove workable it promised direct control of the spots and a simple means of controlling instrument sensitivity by the adjustment of the direct voltage across the dividers. It also offered the possibility of grading these resistors so as to make possible sensitivity which varied with angular displacement.

In taking off electrical control voltages from the gyro instruments it is essential that friction and other disturbing forces be kept low, if the gyros are to function properly. The bank and climb gyro is stabilized by gravity, and will eventually return to its proper orientation if displaced, but the directional gyro has nothing but its "memory" to rely on, once it has been oriented. Therefore, the very practical criterion that the frictional and other forces added by the electrical take-off mechanism be small compared to the friction already existing in the gyro mounting, was used as a guide in this work. Doctor C. S. Draper of the MIT department of aeronautics was fortunately able to provide not only the necessary information about commercial gyro instruments, but also the means for measuring the added friction of the electrical take-off. The development of the electrical take-off was carried out largely under his direction by his colleague Doctor J. D. Trimmer. On the basis of their work the simple expedient of obtaining voltages directly from a resistor by a contact brush carried on the gyro mounting ring appeared to be practical. The added friction amounted to about ten per cent of that already in the gyro and produced no detectable effect on the behavior of the instrument. A photograph of the electrical take-off in one of the gyro units is shown in figure 2.

Since the voltage delivered by the gyro instrument was sufficient to deflect the spots on the cathode-ray tube directly, amplifiers with their attendant complexity were unnecessary. As negligible currents were required, the area of contact could be kept very small and contact pressures kept sufficiently high to make the resistor card self-cleaning without producing undue drag. The brushes

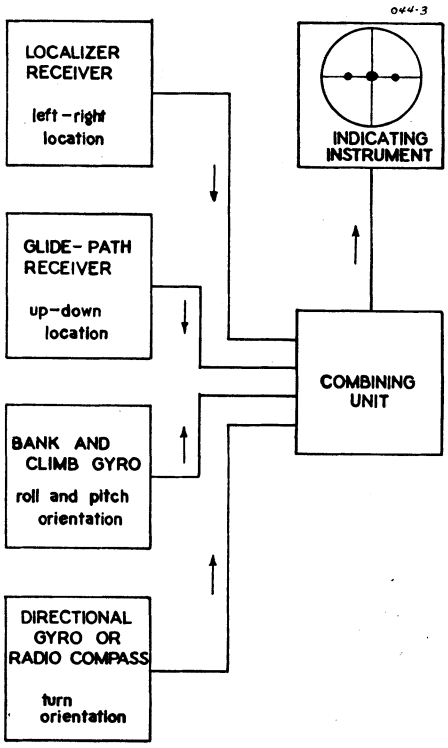

Figure 3. Block diagram of airplane equipment

were shaped from tungsten wire 0.003 inch diameter.

Instead of a three-gun cathode-ray tube, which might at first thought appear to be ideally suited to produce the three-light pattern, a standard tube was used in conjunction with mechanical commutation** to produce the three-gun effect. The control circuit was somewhat simpler and it was also a definite advantage to have only one spot to be focused and centered as well as to have the same sensitivity for each virtual

‡ The work of MIT in the general field of light scattering by fog, including the work done in connection with the instrument landing project, will be published in the near future.

** Electronic commutation was examined; however mechanical commutation was more readily adaptable to this particular instrument.

spot. Furthermore, a wide variety of single-gun tubes were readily available.

These elements were combined as shown in the block diagram of figure 3 which summarizes the broad features of the instrument and indicates their functional interrelationship.

Thus, a method and mechanism have been developed for synthesizing a visual image simulating three lights on the landing field. This system, like any other which makes use of electrically operated indicating instruments, makes possible the removal of the gyro instruments from the instrument panel, the duplication or repetition of their indication at several locations in the airplane, and the concentration of essential landing information on a single instrument. The use of the equipment during flight is also feasible. The instrument gives gyro information and the runway localizer signals may be replaced by range signals.

Finally the instrument indication is not limited to the three-spot image but can, for instance, be in the form of a central

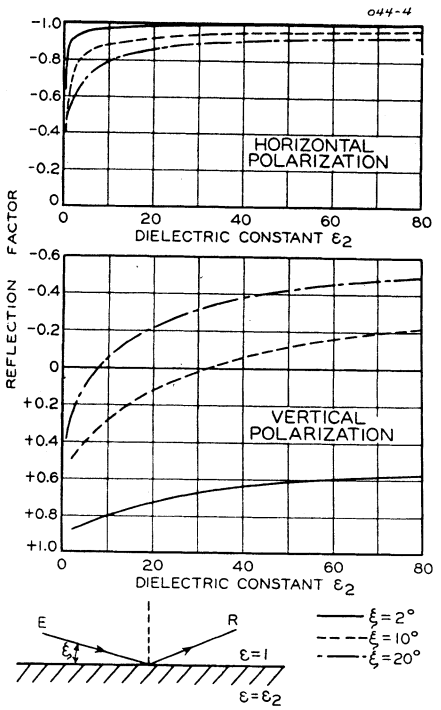

Figure 4. Reflection factor for ultrahigh-frequency waves as a function of dielectric constant

figure moved by the reference path or by the radio range signals and a bar image, simulating the bar on the gyro horizon. The bar image can also be controlled in translation so as to convey not only bank and climb information but also heading. A bar-and-circle pattern has been incor-

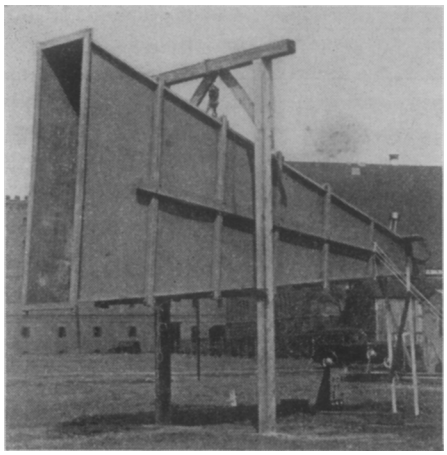

Figure 5. Electromagnetic horn radiator

porated in the Flightray[2] developed by the Sperry Gyroscope Company, Inc.*

The Landing Reference Path

A straight-line landing reference path with an adjustable angle of from three to six degrees with respect to the horizontal was desired. It was recognized at the outset that to realize this path relatively free from ground, weather, and reflection effects highly directive component beams would be required. This would be particularly true for the lower of the two beams making up the glide path. To fulfill this requirement by radio means called for wave lengths as short as possible in order to obviate radiating systems of undue physical size. A comparative investigation was therefore made of broadside and end-fire arrays of half-wave elements, long-wire antennas, parabolic reflectors, and horn radiators.

Preliminary analysis and tests indicated that a horn of rectangular cross section could by appropriate design be made to produce smooth beams of the requisite degree of directivity in horizontal and vertical planes.[3] On the basis of the results of this investigation the horn type of radiator was selected because it was simpler to adjust, freer from spurious radiation from feed wires, and had inherently a better radiation pattern than was obtainable from the other devices examined.

Even with wave lengths as short as 50 centimeters and antennas of reasonable size, it is not possible to produce landing beams of sufficient sharpness to be entirely free from the effects of reflected energy from the ground. It was therefore desirable to determine which of the two polarizations, horizontal or vertical, would make these reflections least. Past experiments with instrument landing systems had resulted in a divided opinion as to the preference of one polarization over the other for this service. A theoretical investigation of this problem was therefore carried out to aid in selecting proper polarization. The earth may be treated with a fair degree of accuracy as a perfect dielectric for the ultrahigh frequencies employed in this system. Its effect may be expressed by means of a reflection factor, equal to the ratio of the intensity of the wave reflected from it to that incident upon it. A change in the physical condition of the earth caused by rain, drought, sleet, and snow is accompanied by a change of the dielectric constant. That polarization will be preferable which causes the least change in reflection factor for given changes in the dielectric constant. A typical set of curves showing the variation of the reflection factor with the dielectric constant for several angles of incidence is reproduced in figure 4. Clearly, horizontal polarization provides the more uniform behavior with changing ground conditions. Since making this study, confirmatory experimental evidence from several sources has been obtained in favor of horizontal polarization of beams for instrument landing.

Making use of a theory of horn design

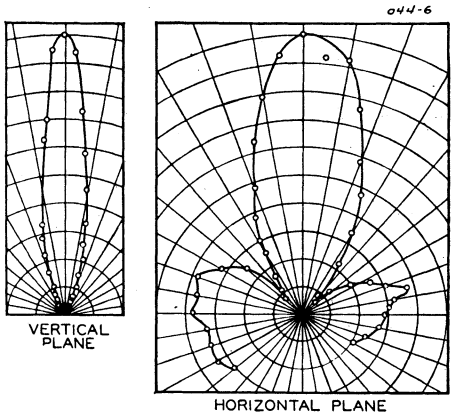

Figure 6. Measured relative electric intensity in vertical and horizontal planes for the horn of figure 5

evolved in a separate research program[4] a horn was constructed specifically for the production of a landing beam. The body of the horn was made of three-eighth-inch bakelite-bonded plywood and was lined inside with thin copper foil. Figure 5 shows the completed horn. It is about

* The Sperry Gyroscope Company at about the time the MIT program was developed undertook the development of a cathode-ray-tube flight instrument which included information from the gyro group. It is with pleasure that we acknowledge here the cordial constructive exchange of ideas with this organization in connection with related aspects of our project.

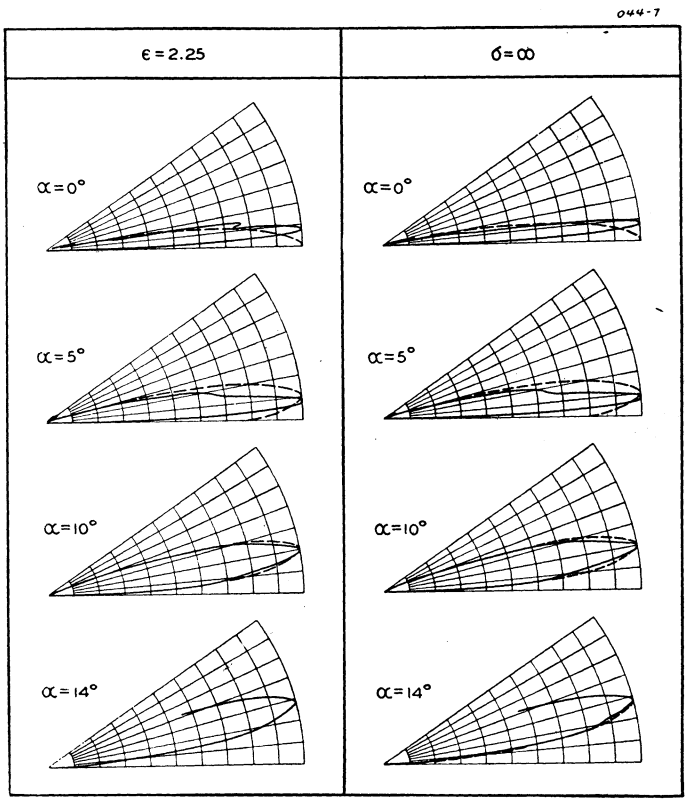

Figure 7. Calculated effects of a perfect dielectric earth ($\epsilon = 2.25$) and a perfectly conducting earth ($\sigma = \infty$), on horizontally polarized radiation from the horn of figure 5. Axis of horn inclined at the angle α; mouth resting on the earth

26 feet long by 10 feet high by 2.5 feet wide (at the mouth) and has an angle of flare of 20 degrees in the direction of height. At a wave length of 50 centimeters this corresponds to a height of 6 wave lengths and a width of 1.5 wave lengths. The theoretical power gain compared to a Hertzian doublet is 50. The exciting antenna is a straight wire about one-quarter wave length long placed in the throat. Figure 6 shows measured radiation patterns of this horn in the vertical and in the horizontal planes under substantially free-space conditions. The vertical pattern is notably free from secondary lobes. The horizontal pattern has been made sharp and the secondary lobes have been tolerated for sake of power gain. The preferred pattern in this plane, were less power gain satisfactory, would have a single broad lobe. A beam of this character could be obtained by reducing the width of the horn.

The next step was to determine the best position of the horn with respect to the ground for the production of a landing beam. Patterns were therefore calculated for different heights of the horn above ground, for different angles of the axis of the horn with the horizontal, for perfect dielectric and perfectly conducting earths, for horizontal and for vertical polarizations, and for different sizes of horns. Examples of these patterns are shown in figure 7. Measurements of radiation patterns were made with the aid of captive balloons. These measurements agreed well with the theoretical predictions. From these calculations and measurements it appeared that the disposition of two identical horns for the glide path beams might be as follows: the lower edges of the mouths of both horns touch the ground, with one horn at an angle of elevation of five degrees, and the other at an angle of ten degrees. With this disposition, additional sharpness of the lower beam is obtained at present by helpfully utilizing the reflections from the ground. When transmitting with equal strength, these two horns should yield a glide path angle of about six degrees; a smaller angle could be obtained by reducing the power output or the modulation of the lower horn. A pair of horns of the type shown in figure 5 was set up in the field in accordance with this information. These radiators were fed from separate triode oscillators operating at slightly different frequencies and modulated at 90 and 150 cycles per second respectively. Balloon measurements of the resultant equisignal straight-line glide path were then made over a distance of 700 feet with highly satisfactory results as indicated in figure 8. Its angle with the ground was adjustable at will to values between 6 and 11 degrees by adjusting the relative sensitivities of the 90- and 150-cycles-per-second audio channels of the receiver.

Excitation of Beam Radiators

In the equisignal beam tests separate transmitters operating at slightly different carrier frequencies were used to excite the two horn radiators in order to avoid space interference of the carriers and to obviate any difficulty of cross modulation. Cross modulation would cause a broadening of the on-course or equisignal zone. Cross modulation through a common power source could be avoided by the use of buffer amplifiers, or by a bridge connection[5] of the two output lines to a single power source. Numerous tests have established that there is no appreciable mutual impedance effect between the horn antennas employed here. In the absence of phase modulation, space interference between the two radiated carriers occurs if both radiators are fed from a common source. Such interference does not take place between the two pairs of side bands for they are of different frequency. The two horns used in these tests were separated in space by several wave lengths. Strong lobes and zeros might therefore have been produced in the horizontal radiation pattern had a common modulation source been used. In some systems this trouble is avoided by juxtaposition of the antennas in space; in others it is probable that some reduction occurs from phase modulation introduced by mechanical modulation. It is expected that further investigation will establish that a single source may be successfully used in the specific system described in this paper. The use of separate oscillators is open to objection principally because it doubles the transmitting apparatus.

For most of the experimental investigations carried on during this research,

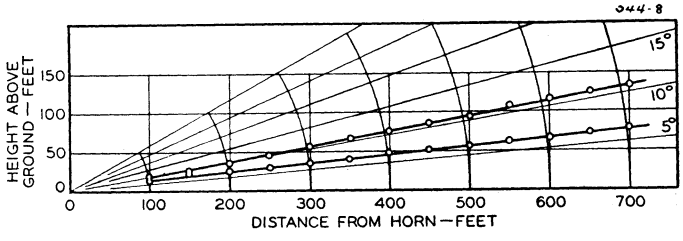

Figure 8. Balloon measurements of equi-signal paths. The two paths correspond to different adjustments of the audio channels of the receiver

simple low-powered oscillators[6] were employed as sources. These oscillators used the Western Electric 316-*A* triode in a feedback circuit with short-circuited coaxial transmission lines as circuit elements. They operated at wave lengths from several meters down to the limit of oscillation of the tube (about 40 centimeters) delivering about five watts at 50 centimeters and about one watt at 42 centimeters. These small amounts of power when used with sharply directive horn radiators have proved sufficient both for measurement of radiation characteristics with very simple detectors and for flight tests. Modulation of the radio-frequency output was accomplished by inserting in series with the direct plate voltage an audio-frequency voltage obtained from a vacuum-tube oscillator-amplifier unit. When overlapping radio beams were used for production of glide-path signals, the oscillators were modulated at 90 and 150 cycles per second respectively. Voltage-regulated power supplies in both plate and filament circuits of the oscillators were necessary for the production of stable signals. With constant voltages applied to the oscillators and with reasonable care in their adjustment, however, the frequency drift was small enough so that the oscillators would operate for several hours without retuning them or the receiver.

The first application of the "klystron" outside the Stanford Laboratories was made in this research through the courtesy of the Sperry Gyroscope Company, Incorporated, Stanford University, and the United States Army. Oscillators of this general type[7] are capable of producing several hundred watts of power at wave lengths in the neighborhood of 40 centimeters with an efficiency considerably greater than that of ordinary vacuum-tube circuits operating in the same wave-length range. Modulation of the klystron oscillator was accomplished either by variation of the voltage accelerating the electron beam, or by modulation of the radio-frequency output

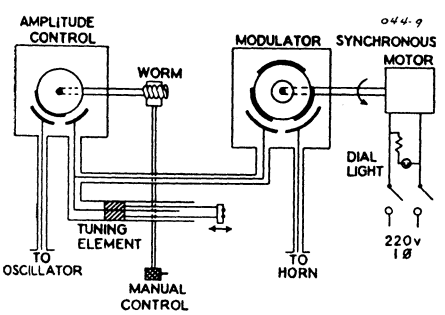

Figure 9. Schematic diagram of transmission-line modulator

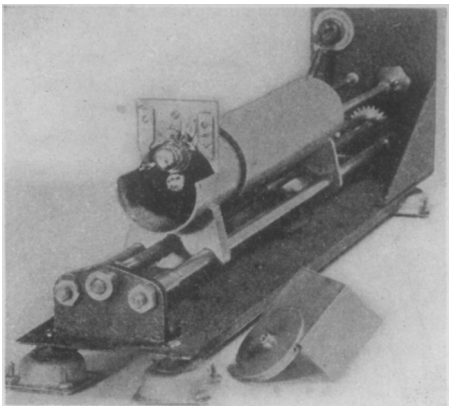

Figure 10. Triode grid-leak detector with cover removed

in the transmission line connecting the klystron to its load.

For modulation in the transmission line, a mechanical modulator of the type shown in figure 9 was developed. The operation of this type of modulator is based on the fact that a variable capacitor inserted in series with the center conductor of a coaxial transmission line may be used to control the power transmitted through the line. A capacitor is rotated at such a speed that its reactance is varied at the desired modulation frequency, thus modulating the power delivered to the load. A second series capacitor, adjusted manually, serves as an amplitude control to determine the average amount of power transmitted through the modulator. An additional control is provided in the form of a short-circuited coaxial transmission line of adjustable length, connected across the transmission line between the amplitude control capacitor and the modulating capacitor. When correctly adjusted, the modulator will produce very nearly sinusoidally modulated signals with a modulation factor of about 0.95.

The Airplane Receivers

A preliminary calculation showed that a power of less than one watt delivered to an antenna with a power gain of 30 would produce a signal of one millivolt per meter at seven miles if free-space conditions prevailed. This is a fairly strong signal even for simple superheterodyne receivers. With a receiver of this sensitivity adapted for 600 megacycles, ranges of about five miles should be possible with at least one currently available triode (Western Electric 316-*A*). Since a power gain of 50 is provided in the actual antenna, distances of five to ten miles should therefore be expected. On the other hand, if a great deal more power is available at the transmitter, much simpler receivers should prove satisfactory.

The ultrahigh frequencies (approximately 700 megacycles) used necessitated the development of special radio receiving equipment for use in the airplane. The first receiver constructed was a triode grid-leak detector followed by an audio amplifier. A photograph of this unit with the cover removed is shown in figure 10. This simple receiver was satisfactory for use with a high-powered transmitter such as the klystron, but experience with it demonstrated that greater sensitivity and greater freedom from vibration effects would be very desirable. A novel superheterodyne receiver which fulfilled both of these requirements was therefore constructed.

In this superheterodyne receiver the 700-megacycle signal is fed directly into the converter which mixes the incoming signal with the third harmonic of the local oscillator and produces a 10-megacycle beat-frequency signal. This beat frequency is fed to the intermediate-frequency amplifier where it is amplified with no greater difficulty than any other 10-megacycle signal. The converter uses a diode and a combination of lumped and distributed circuit elements that are tuned to the frequencies of the 700-megacycle signal, the 230-megacycle local oscillator, and the 10-megacycle intermediate-frequency amplifier. An equivalent circuit diagram of the converter is shown in figure 11. The circuits *A*, *B*, and *D*, are all connected in series with the diode in such a manner that a voltage appearing in any one of them is impressed across the diode substantially independently of those appearing in the others. This independence is accomplished by making use of the difference in impedance of the

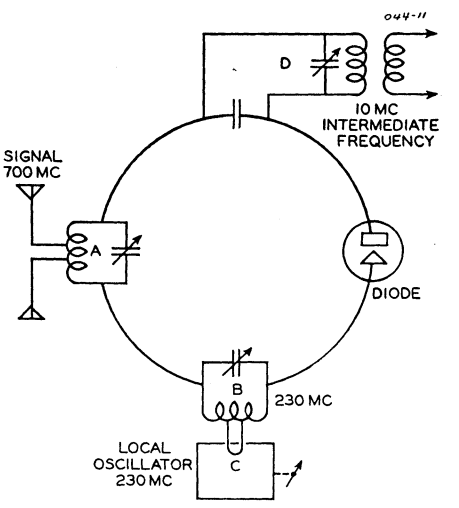

Figure 11. Equivalent circuit of converter of the superheterodyne receiver

three tuned circuits at widely separated frequencies. The local oscillator voltage is fed into the 230-megacycle circuit, *B*, and the diode generates in itself the third harmonic needed to mix with the 700-megacycle signal from circuit *A*. The special diode (*D*157653) used in this circuit was made available to us by the Western Electric Company.

The local oscillator *C* is of the type developed by A. P. G. Peterson[8] with the exception that the negative high-voltage lead is grounded to make possible the installation of the oscillator on the receiver chassis. The tube used is an RCA 955. The oscillator frequency is approximately 230 megacycles, adjustable over a small range. This frequency is low enough so that relatively stable oscillations may be obtained. Since the oscillator frequency is so far removed from that of the incoming signal, there is no danger of the oscillator synchronizing or locking-in with the received signal.

The 10-megacycle intermediate-frequency amplifier consists of two 1852 stages feeding a 6*SQ*7 second-detector audio-amplifier tube. A small amount of automatic volume control is incorporated in this amplifier, which has a gain of roughly 5,000 and a band width of approximately 300 kilocycles.

An elaborate audio-frequency amplifier follows the superheterodyne receiver proper and incorporates four stages of resistance-coupled amplification with automatic volume control, a separating filter for 90 and 150 cycles per second, separate one-stage amplifiers following the filter, and a copper-oxide rectifier system to feed a d-c indicating meter. The audio automatic volume control was provided mainly to allow the use of this amplifier with the grid-leak detector unit which has no automatic volume control of its own. The regulation is such that the output is substantially constant for audio inputs between three millivolts and three volts. A narrow pass band (50 to 400 cycles per second) in the resistance-coupled stages is used to gain freedom from microphonics and motorboating. The output of this audio unit is fed to the adapter unit of the cathode-ray indicator, and the rectified direct current from the copper-oxide rectifier is connected to a zero-center crossed-pointer meter for glide-path indication.

A control is provided to allow adjustment of the relative gain of the two audio channels. The setting of this control determines the angle of the glide path with respect to the ground. This control may be set so that the approach path

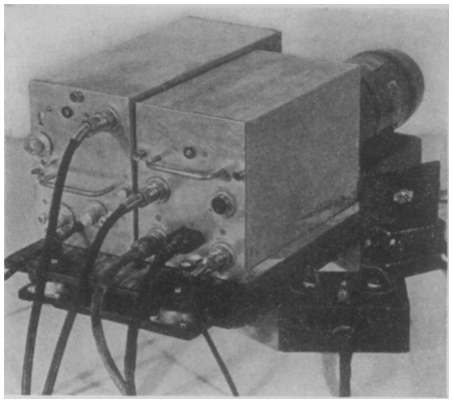

Figure 12. Complete superheterodyne receiver

angle is correct for a given type of airplane. This arrangement does not require a readjustment of the ground station to set the glide angle.

The complete superheterodyne receiver was mounted on a plywood board supported by double shock-proof mountings —an arrangement which was fairly effective in suppressing vibration. A photograph of the equipment as it was installed in an airplane for flight tests is shown in figure 12.

The antenna was a coaxial type[9] connected to the receiver by a one-quarter-inch copper coaxial line. A short section of the line next to the receiver was made flexible to prevent transmission of mechanical vibration.

Flight Tests

Exploratory flight tests of a beam from a single horn were made at the Boston Municipal Airport mainly to determine workable range with a klystron power source and the simple receiver of figure 10. These tests also demonstrated that a substantially straight constant-intensity glide path could be realized by means of a single-horn radiator. Signals were received up to a distance of eight miles and simulated instrument landings were made repeatedly on this beam by the constant-intensity method over distances of about four miles.

Flight tests of the complete system were made in September 1939.* Two horns, energized by separate low-power triode oscillators, were used to provide the overlapping-beam pattern. Utilizing the superheterodyne receiver and the instrument already described, a straight-line landing path at an angle of about three degrees with the ground was flown consistently over a distance of somewhat more than five miles. These tests established the straightness of the microwave path over its entire length, and the feasibility of using the cathode-ray indication and three-light illusion as initially contemplated.

At this same time a klystron was again made available. With an estimated power of 50 watts supplied to one of the horns and using the superheterodyne receiver, flight tests demonstrated that extremely strong signals were received at a distance of 25 miles and an altitude of 2,500 feet. This performance leads us to believe that usable landing signals may be obtained at distances of the order of 50 to 75 miles.

Conclusions

In the course of the solution of the problem set forth at the beginning of this paper a landing system has been evolved embodying both a unique indicating instrument and landing path. The two elements, although used in combination in the system described, can also be applied independently. For example, the instrument may be used with constant intensity glide path and the straight-line glide path may be used with a conventional crossed-pointer instrument.

The landing path described in this paper marks a significant advance not simply because it is straight, and of an equisignal nature, but because it demonstrates a means by which a path essentially free from the effects of ground and surrounding objects may be realized. In this respect also the system describes an advance over conventional ones.[10]

The radio beam being thus substantially free from the effects of its surroundings makes the landing path reproducible and therefore makes the system truly portable.

The beams used for this landing path have other applications. For instance they may be utilized as vertical markers† where they are of value because of their extreme sharpness.

Not many years ago it would have been improvident to predict that within one year a practical 50-centimeter landing system based on the experimental type described here could be installed for pilot training, and it would have been heresy to say that within two years a 10-centimeter system could be made

* The system as projected contemplated the use of centimeter waves for both pairs of beams. It was felt however that a standard localizer could also be utilized. This was done in these tests for which an Airtrack localizer was lent and operated by the Washington Institute of Technology.

† In this research horn radiators were used as markers both singly and in pairs. It is safe to say that the radiated pattern may be made as sharp as necessary by suitable design. The use of the modulated cross beams yields an approach signal, an instantaneous "over the marker" signal, and a departure signal.

available for this purpose, yet now such is our confidence that on the basis of contemporary developments in the industry and elsewhere these predictions may now be made with reasonable assurance of fruition.

In conclusion we wish to acknowledge the interest of the United States Army and the industry in this project. The Army made itself familiar with the work not long after its inception and has since, through co-operation, confirmed many of our observations. This interest can, we think, be taken not only as an index of the importance of centimeter-wave technique in air navigation but also as a recognition of the possibilities of research on critical problems through the co-operation of the government and the industry with technical institutions such as the Massachusetts Institute of Technology.

Bibliography

1. THE EFFECT OF RAIN AND FOG ON THE PROPAGATION OF VERY SHORT RADIO WAVES, **J. A. Stratton.** IRE *Proceedings*, volume 18, June 1930, page 1064.

ON THE LOCAL DISSIPATION OF NATURAL FOG, **H. G. Houghton and W. H. Radford.** MIT Woods Hole Oceanographic Institute, volume 6, number 3, October 1938.

TRANSMISSION OF ELECTROMAGNETIC WAVES IN HOLLOW TUBES OF METAL, **W. L. Barrow.** IRE *Proceedings*, volume 24, October 1936, page 1298.

2. "FLIGHTRAY," *Communications*, volume 18, October 1938, page 22.

3. THE SECTORAL ELECTROMAGNETIC HORN, **W. L. Barrow and F. D. Lewis.** IRE *Proceedings*, volume 27, January 1939, page 41.

THEORY OF THE ELECTROMAGNETIC HORN, **W. L. Barrow and L. J. Chu.** IRE *Proceedings*, volume 27, January 1939, page 27.

4. ELECTROMAGNETIC HORN DESIGN, **L. J. Chu and W. L. Barrow.** AIEE TRANSACTIONS, volume 58, 1939 (July section) page 333.

5. United States Patent 2,147,809, A. Alford.

6. AN OSCILLATOR FOR ULTRAHIGH FREQUENCIES, **W. L. Barrow.** *RSI*, volume 9, June 1938, page 170.

7. A HIGH-FREQUENCY OSCILLATOR AND AMPLIFIER, **R. H. Varian and S. F. Varian.** *Journal of Applied Physics*, volume 10, May 1939, page 321.

VELOCITY-MODULATED TUBES, **W. C. Hahn and G. F. Metcalf.** IRE *Proceedings*, volume 27, February 1939, page 106.

AN ULTRAHIGH-FREQUENCY POWER AMPLIFIER OF NOVEL DESIGN, **A. V. Haeff.** *Electronics*, volume 12, February 1939, page 30.

8. HIGH-Q TANK CIRCUIT FOR ULTRAHIGH FREQUENCIES, **A. P. G. Peterson.** *QST*, volume 23, September 1939, page 19.

9. COAXIAL ANTENNA, IRE *Proceedings*, volume 27, January 1939, page 11.

10. A RADIO BEACON AND RECEIVING SYSTEM FOR BLIND LANDING OF AIRCRAFT, **H. Diamond and F. W. Dunmore.** IRE *Proceedings*, volume 19, April 1931, page 585.

WIRELESS DIRECTION FINDING (a book), **R. Keen.** Third edition, chapter 15, Iliffe and Sons, 1938.

REPORT ON THE STATUS OF INSTRUMENT LANDING SYSTEMS, **W. E. Jackson.** Bureau of Air Commerce, Report No. 1, October 1937.

Discussion

For discussion, see page 1120.

Compressed Powdered Molybdenum Permalloy for High-Quality Inductance Coils

V. E. LEGG
MEMBER AIEE

F. J. GIVEN
ASSOCIATE AIEE

Synopsis: Molybdenum-Permalloy is now produced in the form of compressed powdered cores for inductance coils. Its high permeability and low losses make possible improved quality or decreased size without sacrificing coil performance. Its low hysteresis loss reduces modulation enough to permit application where large air-core coils would otherwise be required.

THE introduction of loading coils in the telephone system at about the turn of the century brought special demands on magnetic and electrical properties of core materials, and set in motion investigations which have had wide influence on the theoretical and practical aspects of ferromagnetism. The first step in this development led to cores of iron wire, which sufficed for loading coils on circuits of moderate length.[1] With the development of telephone repeaters and the extension of circuits to transcontinental length some 25 years ago, there arose need not only for loading coils, but also for network coils, which would have high stability with time, temperature, and accidental magnetization. Magnetic stability was at first secured[2] by employing iron-wire cores provided with several air gaps. Later, commercial and technical considerations led to a core structure made from compressed insulated powdered material, first electrolytic iron[3] and later Permalloy powder.[4] This type of core is mechanically stable; it introduces in an evenly distributed fashion the requisite air gaps, while avoiding undesirable leakage fields; and it subdivides the magnetic material so as to reduce eddy-current losses. Although other means have been suggested,[5,6] no way has yet been devised which provides these features so well and at so low a cost as the compressed powdered type of core.

Paper 40-20, recommended by the AIEE committee on communication, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted June 21, 1939; made available for preprinting December 12, 1939; released for final publication February 16, 1940.

V. E. LEGG and F. J. GIVEN are members of the technical staff, Bell Telephone Laboratories, Inc., New York, N. Y.

1. For all numbered references, see list at end of paper.

Loading-coil cores made from electrolytic-iron powder generally satisfied the stability requirements for long lines, but on account of their low magnetic permeability they were large and costly. The search for materials with higher permeability and lower hysteresis loss led to Permalloy[7] which, by 1925, had been produced in powdered form and fabricated into cores. This development provided coils for voice-frequency applications (loading coils and filter coils) which were cheaper and yet superior electrically to those made from electrolytic iron. These coils became available at a time when the telephone plant was undergoing a very large extension of loaded cables. As a result, large economies in cost and space were realized in the more than 6,000,000 coils involved in this plant expansion.

Iron powder, and later Permalloy powder, ground to a finer size and diluted to lower permeability than used in loading coils, also found application in coils for oscillators, filters, and networks of multiplex carrier telephone and telegraph systems employing frequencies up to 30 kilocycles[8] and in receivers for transoceanic radiotelephone communication employing frequencies up to approximately 60 kilocycles.[9] Permalloy powder improved the electrical characteristics—particularly modulation—of coils for use in high-frequency circuits, because of its low hysteresis losses.

Continued research for a powdered material having still better intrinsic properties has recently made available new compressed powder cores which permit further important gains in coils for voice-frequency circuits and in coils for high-frequency carrier system applications. The latter take on considerable significance at this time because they play an important part in making practical for commercial use the new broad-band carrier telephone systems intended for use on existing open wire and cable lines and on new types of cable. Again, therefore, the advent of a new core material is well-timed to be of assistance in further growth of the telephone system.